

## **LIDAR and Numerical Modeling Studies of Small-Scale Lateral Dispersion in the Ocean**

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### **LONG-TERM GOALS**

Our long-term goal is to better understand lateral mixing processes in the ocean on scales of 10 m to 10 km, i.e., the “submesoscale”. We aim to understand the underlying mechanisms and forcing, as well as the temporal, spatial, and scale variability of such mixing. This research will contribute to fundamental knowledge of ocean dynamics at these scales, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

### **OBJECTIVES**

One objective of our work is to determine the extent to which shear dispersion – the interaction of vertical mixing with vertical shear – can explain lateral dispersion at scales of 10 m to 10 km. A second objective is to determine whether slow but persistent vortices enhance the stirring attributable to shear dispersion. We also share the overall objectives of the Lateral Mixing DRI to try to determine the extent to which submesoscale stirring is driven by a cascade of energy down (in wavelength) from the mesoscale, versus a propagation of energy upwards from small mixing events (e.g., via generation of vortices). A key technical goal of our work is to develop the use of airborne LIDAR surveys of evolving dye experiments as a tool for studying submesoscale lateral dispersion.

This annual report marks the end of year 4 of a 5 year study as part of the “Scalable Lateral Mixing and Coherent Turbulence” (a.k.a., LatMix) DRI. The main effort of the present work is a collaboration between J. Ledwell and E. Terray (WHOI), M. Sundermeyer (UMass Dartmouth), and B. Concannon (NAVAIR). This project is also being performed jointly with a collaborative NSF grant to J. Ledwell, E. Terray, and M. Sundermeyer (see “Related Projects” below). ONR support for this work included the airborne LIDAR operations as well as a substantial part of the field operations and analysis.

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## APPROACH

Our approach is to release dye patches on an isopycnal surface in the seasonal pycnocline, and along the Gulf Stream front, and to survey their evolution for periods of 1 to 6 days, in collaboration with other investigators in the DRI. Two major field experiments have been conducted under the LatMix DRI, one 21 day experiment in the Sargasso Sea in June 2011, and one 25 day experiment along the north wall of the Gulf Stream in Feb/Mar 2012. Both efforts were multi-ship, multi-investigator efforts, of which the dye, drifter, and lidar work under this project were one part. Ongoing analysis of data from these field efforts is a collaborative effort between the field PIs, numerical modelers, and theoreticians.

In the context of the DRI modeling efforts, M. Sundermeyer is also collaborating closely with M.-P. Lelong in support of her DRI grant, “LES Modeling of Lateral Dispersion in the Ocean on Scales of 10 m – 10 km.” As part of this, numerical simulations and analysis are being performed under the present effort in preparation for, and to aid interpretation of, the main field studies. These numerical simulations are also being coordinated with modeling efforts of other DRI participants.

## WORK COMPLETED

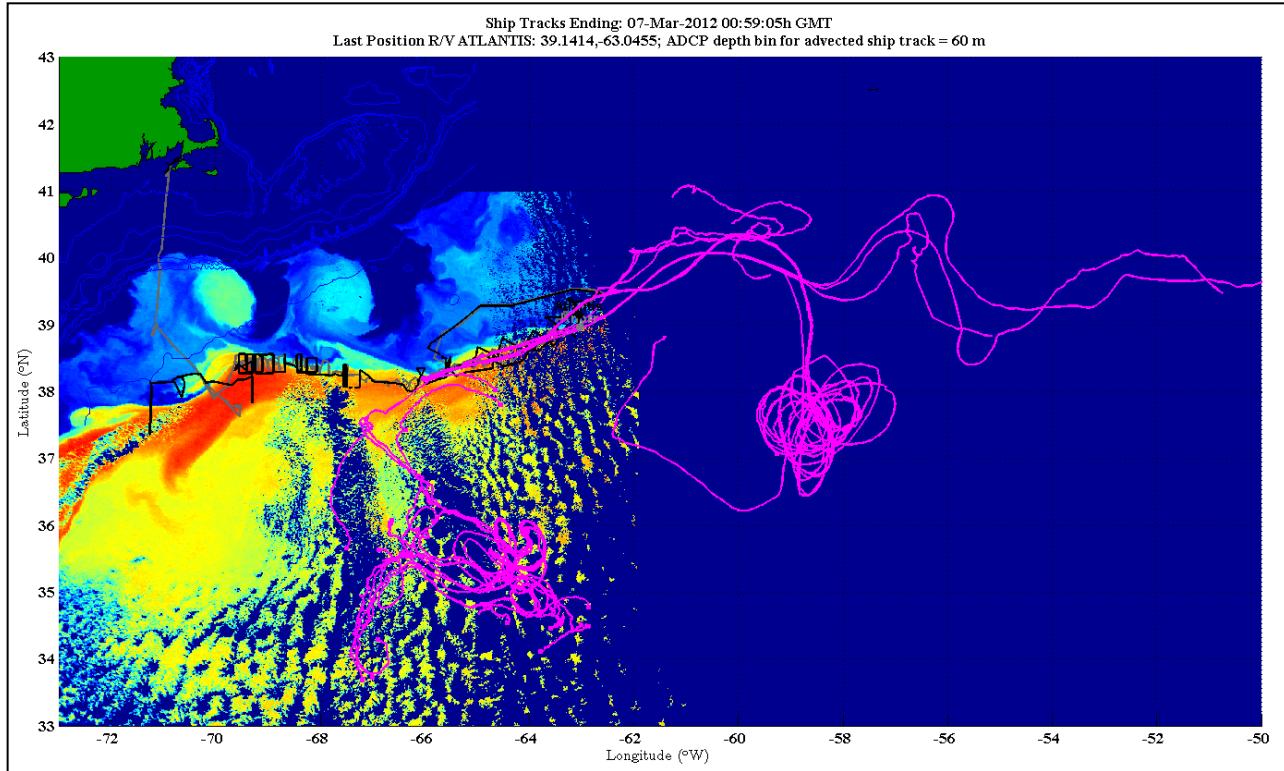
A data analysis and planning meeting for the LatMix DRI was held in Portland, OR in January, 2012, chaired by J. Ledwell. The main objectives of this meeting were to collaborate on ongoing data analysis relating to the June 2011 field experiment, and to finalize plans for the Feb/Mar 2012 field experiment. A second data analysis meeting / workshop was held in Woods Hole, MA in June, 2012 to share results from both the 2011 and 2012 field efforts, and to enhance collaborations relative to data, modelling and theoretical analysis.

Analysis of the 2011 field data is ongoing. A description of the experimental approach, the various components of that experiment, and the roles of our numerous DRI collaborators was provided in our FY2011 annual report, and is not repeated here. In brief, over the past year, our analysis of the 2011 field data has focused on the following:

- 1) Analysis and interpretation of the 2011 in situ dye sampling data collected from the UMass Dartmouth Acrobat sampling system.
- 2) Analysis and interpretation of the 2011 UMass Dartmouth and accompanying NOAA drifter data (all deployed with the dye).
- 3) Processing and analysis of the 2011 LIDAR data set, with emphasis on inversion of the fluorescein dye signal.

The second major field experiment of the LatMix DRI occurred from Feb 22 – Mar 17, 2012. As with the 2011 field effort, this was a multi-ship, multi-investigator effort. The R/V *Knorr* was the “lead” ship, with C. Lee (APL/UW) as Chief Scientist of both the cruise and the experiment. Dr. Lee’s efforts focused on hydrographic and dye surveys around Lagrangian floats deployed by E. D’Asaro (APL/UW), with material and theoretical support from L. Thomas (Stanford Univ.). Our part of the 2012 experiment was conducted from R/V *Atlantis*, with J. Klymak (Univ. Victoria) serving as Chief Scientist and running the MVP hydrographic sampling; and M. Sundermeyer (UMass) coordinating dye releases, with assistance from B. Guest and L. Houghton (WHOI). Also onboard R/V *Atlantis* was

D. Birch (UMass), coordinating data collection of dye and hydrography via both the R/V *Atlantis* and R/V *Knorr* flow-through systems. The drogued drifter program was led by Sundermeyer, with assistance from D. Birch. Glider sampling was led by K. Shearman of Oregon State Univ.



**Fig. 1. LatMix 2012 study region showing example ship tracks during departure from Woods Hole, MA, and one ‘drift’ of Lagrangian float and dye / drifters. R/V Atlantis ship track is shown in black, R/V Hatteras ship track in grey. Drifter trajectories for all drifter deployed during cruise are shown in magenta. Note Gulf Stream ring separation (~59 °W, 37 °N) vs. Gulf Stream extension trajectories (~59-50 °W, 40 °N), and large cluster of 17 NOAA drifters released in ‘mesoscale soup’ region (~65 °W, 35 °N)**

The primary goal of the 2012 LatMix field experiments was to quantify and identify processes controlling submesoscale lateral dispersion across a strong front, including during strong forcing conditions. The general approach of the experiments was to release a Lagrangian float, followed by gliders, dye and drogued drifters, along a particular isopycnal, either at depth or as it outcropped along the north wall of the Gulf Stream. Both ships then conducted intensive surveys of the dye, hydrography, and velocity structure by making repeat surveys / transects across the flow, in a reference frame following the Lagrangian float. R/V *Knorr* focused primarily on tracking the Lagrangian float in real time, and sampling the near field (within a few km) around the float, while R/V *Atlantis* performed larger scale surveys (~10 km) and tended the gliders. Both ships sampled dye via flow-through fluorometers, and R/V *Knorr* via towed triaxus. (Unfortunately, due to instrument problems, R/V *Atlantis* was not able to track the dye using the U. Victoria MVP due to irreparable instrument issues early in the cruise.) An example of ship tracks for the coordinated operation during one of the drift/dye experiments, overlaid on satellite derived SST measurements, and showing drifter trajectories for the duration of the cruise, is shown in Fig. 1.

A total of four dye and drifter releases were performed during the 2012 field effort, two near the surface (~25 m depth), and two at depth (~55 m, and ~120 m depth). A typical experiment was executed as follows. Both R/V *Knorr* and R/V *Atlantis* conducted scouting surveys to determine where to deploy. R/V *Knorr* deployed the Lagrangian float, followed typically within an hour by one or more gliders. R/V *Atlantis* would then position either up- or down-stream of the Lagrangian float, and inject dye along a narrow streak as close as possible to the most up-to-date position of the Lagrangian float, both in depth and Lat, Lon coordinates. Post injection analysis revealed the initial dye streaks to be typically within of order ~0.5 km of the Lagrangian float. Complete surveys of the dye patch were not made. Rather, sampling focused primarily on characterizing the hydrography, velocity, and hence dynamics around the Lagrangian float. As the dye was injected very close to the float, however, repeat transects through the dye patch, and across the stream were obtained, both throughout the water column (R/V *Knorr* triaxus measurements), and from both ship's flow through fluorometers. Analysis to date of the dye results has focused on identifying the pathways of transport and mixing of the dye (e.g., rapidly subducted along isopycnals due to symmetric instability, or pinched off the Stream during the formation of north wall filaments), as well as quantifying along and cross isopycnal dispersion in an environment where isopycnals vary from nearly vertical (outcropping) to nearly horizontal (main pycnocline).

Along with the dye injections, GPS satellite tracked drogued drifters were also deployed with three of the four dye injections. The drifters aided in the overall tracking of the dye patch as it and the drifters separated from the Lagrangian float. They also provided a larger-scale context regarding the velocity and trajectories of fluid parcels along the stream. During the final week of the cruise, an additional large drifter release consisting of 17 NOAA SVP drifters (provided for the cruise by R. Lumpkin, Univ. Miami) was also performed during a 2-day survey of submesoscale variability in the Sargasso Sea south of the Gulf Stream. These drifters will be analyzed in tandem with the fine-scale vorticity analysis lead by A. Shcherbina (APL/UW).

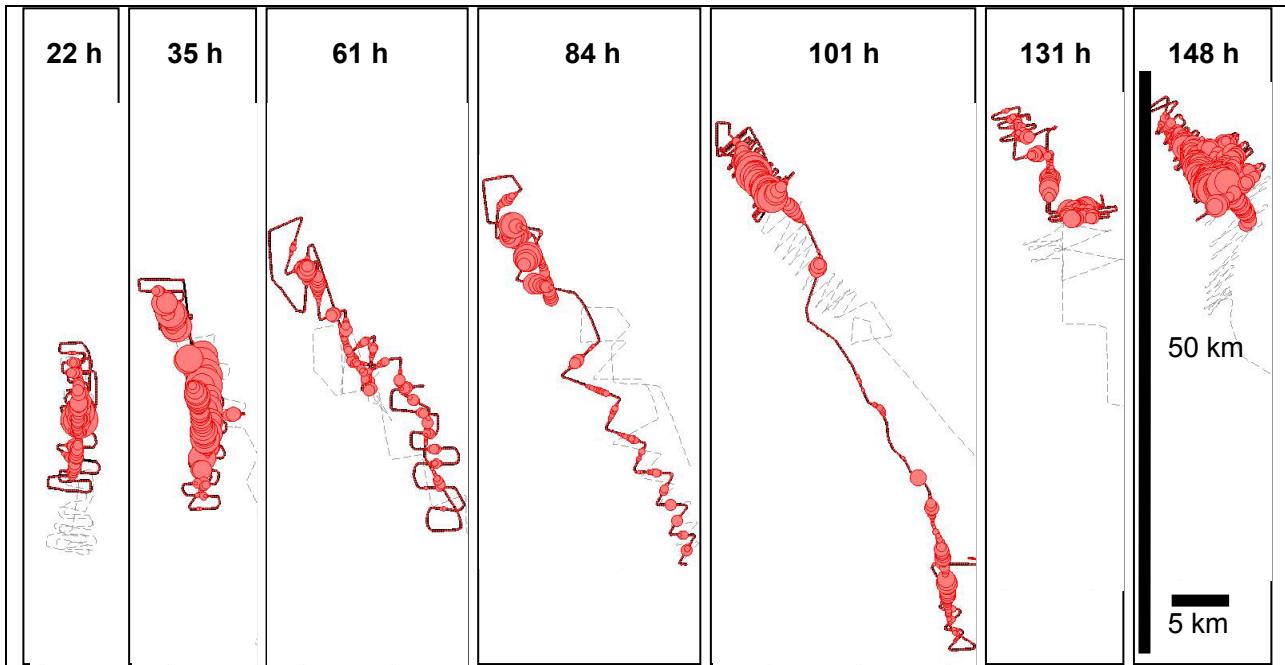
As part of the modeling efforts in collaboration with M.-P. Lelong, we also continue to conduct numerical simulations pursuant to one of the hypotheses of the LatMix DRI, involving localized internal wave breaking and subsequent lateral stirring by the relaxation of diapycnal mixing events. In the present reporting year, one manuscript has been accepted and is in press in *J. Physical Oceanography* on the effect of internal waves on the stability of small-scale vortices generated by patchy mixing, and a second is submitted to *J. Physical Oceanography* on the effect of waves on the inverse energy cascade of vortical mode turbulence. We also continue to examine the effects of large-scale shears and strains, and of intermittency, on the vortical mode stirring mechanism. Additional manuscripts in preparation in collaboration with M. P. Lelong and her student, J. Jacobs, are described in Dr. Lelong's annual report. Overall, the purpose of these simulations is to help guide our interpretation of the field data in distinguishing among different possible lateral mixing processes.

## RESULTS

### *LatMix 2011*

A total of nine dye release experiments were conducted during the June 2011 field effort, two 6-day rhodamine experiments, and seven 26-36 hr fluorescen experiments. The two main rhodamine experiments served to provide a view of the larger-scale (1-10 km, up to as much as 80 km) characteristics of the mixing and strain environment. Meanwhile, the smaller and shorter lived fluorescein experiments provided snapshots of the small-scale variability and early evolution of the

dye dispersal. Approximately daily surveys of the two rhodamine experiments were conducted during the 6 days in which they were tracked. Summary maps of the dye patches for the second of the two main rhodamine experiments are shown in Fig. 2. Primary analysis of both rhodamine experiments reveals diapycnal mixing rates between  $2 \times 10^{-6}$  and  $5 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$  for both experiments. Elongation of the tracer patch, in the zonal direction for the first experiment, and roughly meridionally for the second, revealed strain rates of order  $6 \times 10^{-6} \text{ s}^{-1}$  and up to  $4 \times 10^{-5} \text{ s}^{-1}$  for the first and second experiments, respectively. These values agreed roughly with estimates derived from the drogued drifters released with the dye. Allowing for the effects of strain elongating the patch in one direction, and narrowing it in the other, lateral diffusivities inferred from dye distributions from the two experiments were also similar, ranging from  $0.5\text{-}4 \text{ m}^2 \text{ s}^{-1}$ .

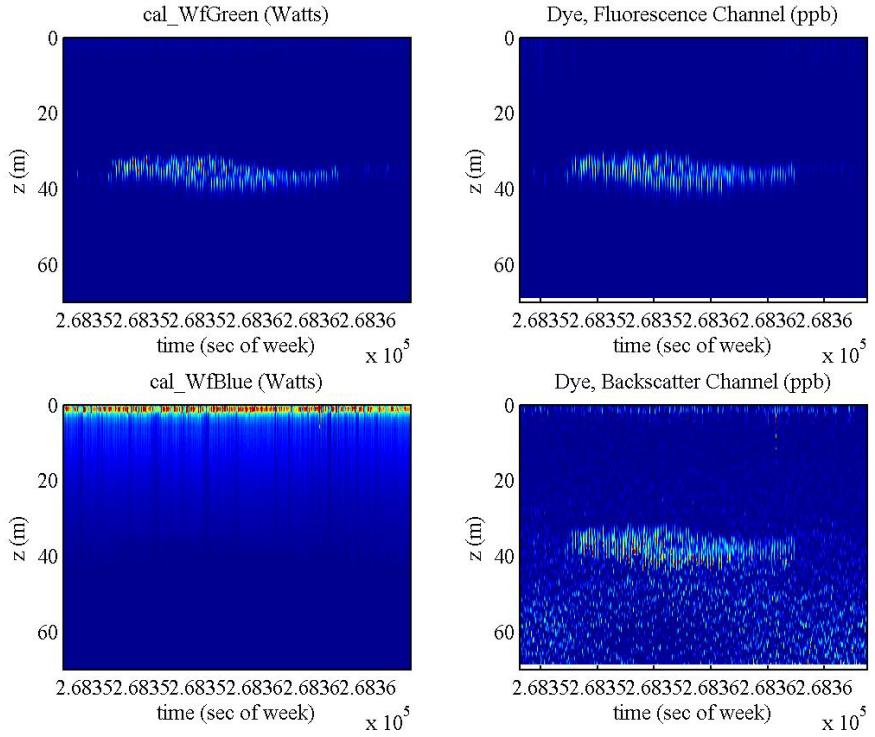


**Fig. 2.** Plan view maps of the second 2012 rhodamine dye experiment as surveyed using the UMass Acrobat tow package over the approximately 150 hrs following release. Successive maps show the elongation and spreading of the tracer patch from its initial release of approximately 1.5 km long x 100 m wide to of order 50+ km long and 5 km wide.

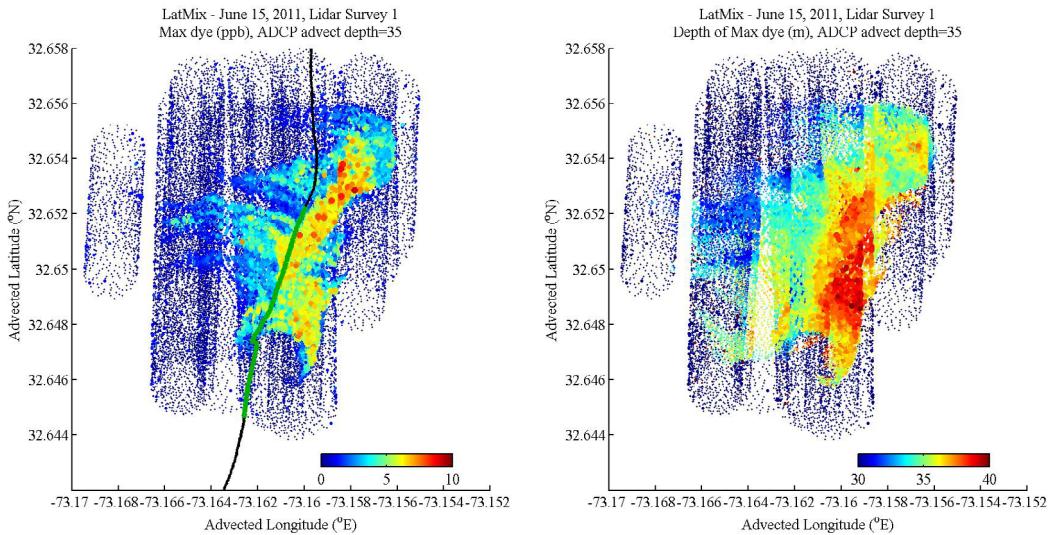
Beyond the above quantitative estimates of diapycnal and isopycnal dispersion rates, a major result from the dye analysis to date is that bulk dispersion estimates derived from the two main rhodamine experiments were found to be larger than could be explained by internal wave shear dispersion. Specifically, an analytical model that incorporates time dependent lateral strain, vertical shear, and a fixed diapycnal diffusivity equal to that derived from the observed dye patches was integrated in time to obtain a best fit to parameters observed in the field observations. Results of the model showed that neither low frequency or steady shears, nor near-inertial or higher frequency shears observed during the experiments, together with the observed diapycnal mixing, could explain the observed lateral spreading of the tracer patches. That high frequency internal wave shear dispersion could not explain the observed lateral dispersion is consistent with findings arrived at independently by other field PIs involved in the larger ONR LatMix effort.

The fluorescein dye patches, typically tracked for between 24 and 36 hrs, were surveyed alternately by the OSU MVP group (M. Levine) and the UMass Dartmouth Acrobat group (M. Sundermeyer), as well as by airborne lidar (led by B. Concannon). M. Levine's group is leading the analysis of the fluorescein in situ data, while M. Sundermeyer and E. Terray are leading the analysis of the airborne lidar data, in collaboration with B. Concannon. Analysis of the lidar data, including improved inversion approaches and in situ calibration to obtain absolute dye concentration, are still ongoing. However, preliminary maps of the dye concentrations by the lidar reveal a rich structure in the dye patches, even early (less than 8 hrs) into the experiments. An example of the lidar signal from a single overflight (one pass over the dye patch) is shown in Fig. 3. The panels show calibrated backscatter (blue wavelength) and fluorescence (green wavelength) lidar returns as a function of time and depth in the water column. Also shown are the results of a preliminary inversion of the dye signal as inferred from each of the two channels using the methods described in Terray and Sundermeyer (2005), and Sundermeyer et al. (2007). The result shows clear signal in both channels, although the raw backscatter dye signal is less clear in this depiction, as there is a background exponential decay of signal with depth.

Plan view maps of the same flight line, along with the remaining passes comprising a complete survey conducted during the June 15 fluorescein experiment, are shown in Fig. 4. Shown in the figure are both peak intensity of dye returns as a function of horizontal position, and depth of the peak return ~2.6 hr after the dye was released. Clear in the image is the dominant north-south orientation of the tracer patch, consistent with the orientation of the initial injection streak. More interesting, however, are the details revealed in the dye patches. These include 1) filamentation of a shallow portion of the dye patch streaming westward in the images, and 2) distinct teasing of the main dye patch, particularly noticeable at its northern- and southern-most extents. The first, the filamentation of the patch in the westward direction, appears to be associated with the shallower portion of the dye patch (as indicated by the depth at which the peak intensity occurred) being sheared westward by the mean current, which shipboard ADCP observations indicate is also to the west. Meanwhile, teasing of the patch, seen as a cyclonic and anticyclonic wisp pair on the southern-most end of the patch, and a distinct curvature along the northeastern most extent of the patch, is suggestive of a scale of stirring of the patch by small-scale (of order 100-200 m) lateral motions. Refined maps of the dye patches as viewed by airborne lidar, and interpretation of the patterns within the patch in the context of other in situ observations is still ongoing. In total, nearly 40 hrs of flight time resulted in mapping of four of the seven fluorescein dye patches, plus one of the rhodamine patches, yielding multiple complete maps of many of these patches.

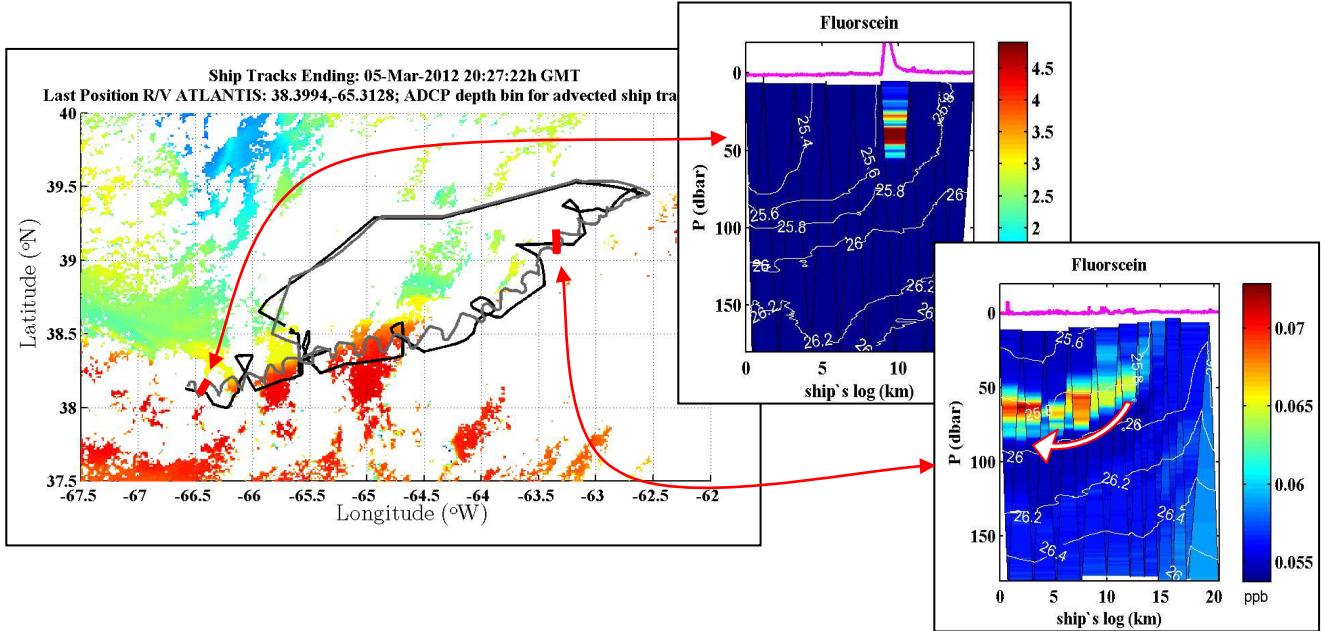


**Fig. 3.** Fluorescence (top left) and backscatter (bottom left) signal from airborne lidar for one pass over the dye patch for the June 15, 2011 fluorescein dye release experiment, and inverted signal for absolute dye concentration (units of ppb) for fluorescence (top right) and backscatter channels (bottom right).



**Fig. 4.** Maximum dye concentration (left) and depth of maximum dye (right) inferred from airborne lidar for June 15, 2011 fluorescein dye experiment. Injection ship track (black) is shown in left panel, advected to the time of the dye survey using the shipboard ADCP observations at 35 m depth (approximate depth of dye surface). Bold green portion of ship track shows where dye was being pumped – i.e., the injection streak. Notable are the shallow (~30 m depth) filaments of dye adverting westward from the main streak, and the tendrils of dye being formed at the southern extent of the patch.

Data reduction and analysis of the 2012 dye and drifter experiments is still ongoing. However, preliminary analysis of the LatMix 2012 data suggests that among the four dye releases, two sampled symmetric instability during strong down-front winds, one sampled an intra-thermocline eddy, and one the separation of a filament along the north wall of the Gulf Stream. For the two symmetric instability experiments, dye was released in the mixed layer at approximately 25 m depth. Within hours after release, the dye was well mixed throughout the mixed layer, and within 24 – 36 hrs, it was mixed down below the mixed layer, to deeper layers where isopycnals become more horizontal than vertical. An example of the early vs. late distributions of the dye along two transects taken during one of these experiments is shown in Fig. 5.



**Fig. 5. Survey map (left) and transect views from one of two near-surface dye release experiments conducted to study mixed layer processes, symmetric instability, and isopycnal mixing along the north wall of the Gulf Stream. Panels to right are transects taken at the beginning and end of the drift, showing fluorescein signals with isopycnals overlaid. The magenta lines at the top of the fluorescein panels show flow-through fluorometer data from R/V Atlantis. Note the subduction and spreading of the fluorescein patch from near the surface, down sloping isopycnals to >60 m depth over the ~36 hrs between the transects.**

For both the intra-thermocline eddy experiment, and the north wall filament experiment, dye was injected below the mixed layer: at ~120 m depth for the first, and ~55 m for the second. For these releases, the dye did not extend to the surface, so that the ship's flow-through systems were not able to measure dye. However, preliminary analysis of triaxus data shows that the dye captured the main features of interest during these drifts. Noteworthy here is that the conditions under which these injections and sampling were performed were among the most difficult ever performed by our group – mean currents exceeded  $2 \text{ m s}^{-1}$ ; vertical shears were of order  $1 \text{ m s}^{-1}$  between the surface and the

injection depth; the dye injection had to target not just a particular isopycnal, but also be as close as possible to the Lagrangian float; injection depths were up to twice that of previous experiments of this type; and all this amid vigorous wind and sea state typical of winter in the North Atlantic.

### ***Modeling Results***

Regarding our modeling work in collaboration with M.-P. Lelong examining the effects of large-scale shears and strains on vortical mode generation and resultant stirring, our major findings to date are that low mode internal wave shears on vertical scales greater than the vortical modes can lead to both barotropic and baroclinic instabilities, which in turn lead to a break-up of the vortices. While this appears to indicate a forward cascade (break-up to smaller scales), when this break-up occurs in a field of vortical modes, the result instead is an inverse energy cascade, fed in part by the internal wave. Furthermore, our initial hypothesis that “low mode waves would arrest any inverse cascade by limiting the extent of vertical coupling of the PV field,” appears to be incorrect. In fact, the internal wave feeds energy into the PV field via baroclinic instability, hence providing more energy to the inverse cascade at that scale. These results are detailed in manuscripts by Brunner-Suzuki, Sundermeyer and Lelong (*J. Phys. Oceanogr.*, In Press) and Brunner-Suzuki, Sundermeyer and Lelong (*J. Phys. Oceanogr.*, Submitted). Additional findings on other aspects of the vortical mode stirring hypothesis in collaboration with M.-P. Lelong (NWRA) and J. Jacobs (UW) are detailed in Dr. Lelong’s annual report.

### **IMPACT/APPLICATIONS**

Our research will contribute to fundamental knowledge of ocean dynamics at the “submesoscale”, and to efforts to properly parameterize sub-grid scale mixing and stirring in numerical models. Ultimately our research will also enhance modeling and understanding of upper ocean ecosystems, since the flow of nutrients and plankton depends on stirring and mixing at these scales.

### **RELATED PROJECTS**

The above work and findings represent a joint effort on the part of LatMix DRI PIs Ledwell and Terray (WHOI) and Sundermeyer (UMass Dartmouth) under ONR grants N00014-09-1-0175 and N00014-09-1-0194, respectively, and Brian Concannon (NAVAIR) under ONR award N0001411WX21010. Furthermore, our work is coordinated with all the other projects within the Lateral Mixing DRI.

Field instrumentation used in the 2011 field work was purchased in part under DURIP grant N00014-09-1-0825, and in part under a related NSF project entitled “Collaborative Research: LIDAR Studies of Lateral Dispersion in the Seasonal Pycnocline”, NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI). The PIs efforts under the ONR LatMix DRI are being performed in coordination with the PIs efforts under the above mentioned NSF Awards OCE-0751734 (UMass) and OCE-0751653 (WHOI).

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